Algorithms for Design of Robust Stabilization Systems

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Abstract. Accuracy of measuring and observation processes depends greatly on the stabilization of the appropriate equipment located on moving vehicles. We propose to design stabilization systems based on robust control that can ensure the required accuracy in difficult conditions of real operation. The main issue of the research is the development of numerical algorithms for designing robust stabilization systems assigned for control of inertial platforms motion. The analysis of applications and classification of inertially stabilized platforms is given. The block diagram of the algorithm of the robust parametrical optimization is represented. Features of this numerical algorithm are discussed including forming the optimization criterion and implementation of the optimization procedure. The block diagram of the robust structural synthesis is represented. Features of forming the function of mixed sensitivity are given. Results of simulation for the inertially stabilized platforms assigned for the operation of the ground moving vehicles are shown.

Keywords: Robust control · Inertially stabilized platforms · Numerical algorithms · Robust parametrical optimization · Robust structural synthesis · Minimum realization · Balanced realization · Function of mixed sensitivity · Weighting functions

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1 Introduction

The topicality of developing numerical algorithms for design of inerially stabilized platforms (ISPs) is explained by the necessity to satisfy the high requirements for stabilization and tracking accuracy. Nowadays, there are two basic groups of the above-mentioned problems [1]:

1) precision stabilization of inertial sensors in gimballed inertial navigation systems;
2) stabilization and tracking of measuring devices and equipment for different purposes;
3) combined stabilization of inertial sensors and measuring devices.

To solve the problem of the inertial stabilization, it is necessary to take into consideration the Earth and moving vehicle motions including the translational speed, and translational and Coriolis accelerations [1, 2]. These factors are taken into account in operating algorithms of gimballed inertial navigation systems. The inertial stabilization of measuring devices and equipment for different purposes requires correction from the inertial navigation systems. Otherwise, this stabilization is considered to be inertial at some approximation.

The block diagrams of the gimballed inertial navigation system and ISP with payload are represented in Figs. 1, 2 [2].

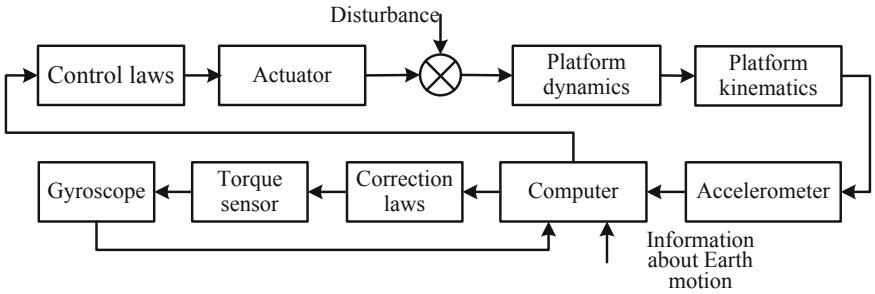

Fig. 1. The block diagram of the gimballed inertial navigation system.

The inertial navigation can be realized by means of both gimballed and strap-down systems [3]. It should be noted that such factors as the drastic progress of inertial sensors (laser, fiber-optic, and MEMS gyroscopes) and computing techniques have been led to the wide application of strap-down inertial navigation systems. This trend was accelerated with arising the possibility to correct inertial navigation systems from Global Positioning System (GPS) [4]. Nowadays, high-precision gimballed inertial stabilization systems are mostly used in strategic applications [3]. On contrary, gimballed systems are important for the stabilization of measuring devices and equipment operated on moving vehicles. Strap-down systems are used in this area only in applications with rigid restrictions on dimensions and low requirements for accuracy [5]. This trend will be kept in the future as efforts directed to the development of measuring devices and observation equipment of high accuracy could be useless without their stabilization [6, 7].

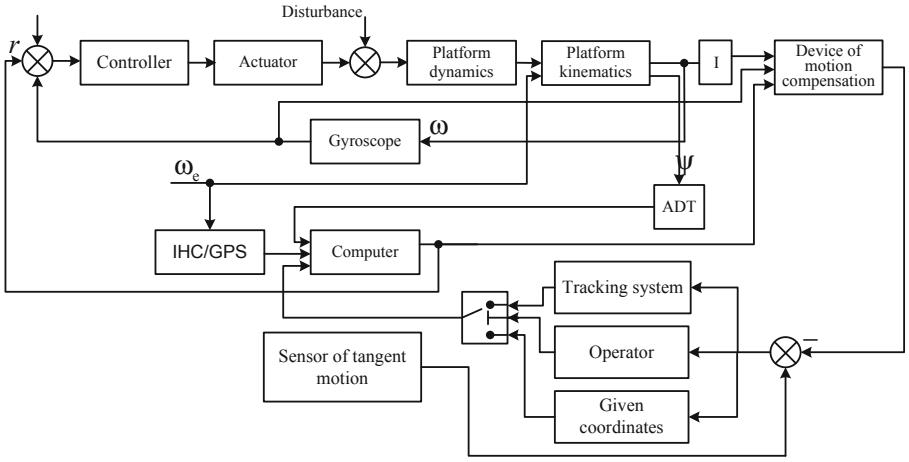

Fig. 2. Block diagram of the inertially stabilized platform: I is the integrator; ADT is the angle-data-transmitter.

Hence, the modern trend of developing ISPs changes accents on types of stabilization systems. Earlier, great attention was paid to the stabilization of inertial sensors. Now, the most topical is the problem of inertial stabilization and controlling orientation by lines-of-sight for measuring devices and observation equipment [8–10].

2 Classification of of Inertially Stabilized Platforms

Systems for control of ISPs can be classified in different ways. One possible classification is shown in Fig. 3. It represents different types of ISPs depending on the presence of a platform, application, stabilization plant, kinematical scheme, type of a drive, and completeness [11]. By application, gimballed and strap-down ISPs are divided into aviation, marine, ground, and portable. By stabilization plant, ISPs can be classified in the following way. There are ISPs for equipment of different purposes, sensors of precision navigation systems, optic sensors, mobile antennas. Depending on the type of the kinematical diagram, ISPs can be one-axis, two-axis, three-axis, and multi-axis. Inertially stabilized platforms can be divided also by the type of drive depending on the presence of the reducer. Features of ISPs for equipment of different purposes depend on payload dimensions, which could vary in the wide range. This factor influences on design and dimensions of the platform and gimbals, and also on the realization of control loops. The typical ISP includes the electro-mechanical unit, which ensures the physical interface between the observation equipment and moving vehicle, stabilization system, and the system of tracking by the line-of-sight of the observation equipment.

An autonomous precision inertial navigation system includes the inertial measuring unit located on the gimballed platform and the computing device. The inertial measuring unit consists of three accelerometers with measuring axes oriented along the platform's axes, and gyroscopic devices, which ensure determining the attitude of the moving vehicle in the inertial space.

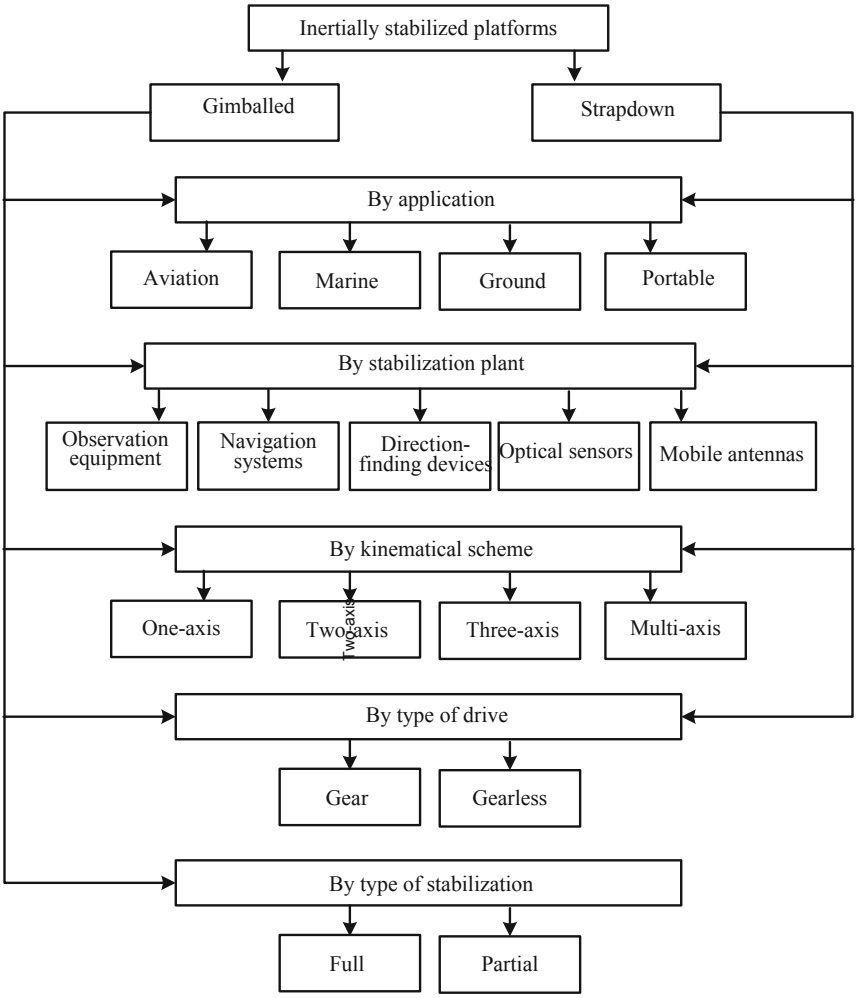

Fig. 3. Classification of inertially stabilized platforms.

The high precision stabilization of optical sensors including television and infra-red cameras can be achieved only if the line-of-sight is controlled [12]. This problem is complicated in conditions of operation of sensors on the moving vehicle or motion of the observation object. Most practical applications of optical sensors in these conditions require stabilization by two axes [1].

Perspective applications of ISPs are control systems of mobile antennas of satellite communication [4]. Nowadays, mobile communication covers practically all the world, but the transmission rate for some applications is not sufficiently high. The increasing rate of data transmission and decreasing cost are possible in conditions of using new satellites able to ensure functioning small satellite terminals. Antennas of satellite communication

of moving small terminals must combine such characteristics as the small aperture, high carrying capacity, high rate of data transmission, and availability by cost maintenance.

The three-axis system ensures the full stabilization of the platform. In this case, the platform's dynamics is described by the Euler equations [13].

$$
\begin{aligned}
M_x &= \dot{\omega} \rightarrow_x J_x + \omega_y\omega_z(J_z - J_y) - (\omega_y^2 - \omega_z^2)J_{yz} - (\omega_x\omega_y + \dot{\omega}_z)J_{xz} + (\omega_x\omega_z - \dot{\omega}_y)J_{xy},\\
M_y &= \dot{\omega}_y J_y + \omega_x\omega_z(J_x - J_z) - (\omega_z^2 - \omega_x^2)J_{xz} - (\omega_z\omega_y + \dot{\omega}_x)J_{xy} + (\omega_x\omega_y - \dot{\omega}_z)J_{xz},\\
M_z &= \dot{\omega}_z J_z + \omega_x\omega_y(J_y - J_x) - (\omega_x^2 - \omega_y^2)J_{xy} - (\omega_x\omega_z + \dot{\omega}_y)J_{yz} + (\omega_x\omega_z - \dot{\omega}_x)J_{xz},
\end{aligned}
\tag{1}
$$

here M_x, M_y, M_z are moments by the gimbal's axes; ω_x, ω_y, ω_z are the platform's rates; J_x, J_y, J_z are inertia moments by the gimbal's axes; J_{yz}, J_{xz}, J_{xy} are axifugal moments; $\dot{\omega}_x$, $\dot{\omega}_y$, $\dot{\omega}_z$ are the platform's accelerations.

Kinematics relationships of the three-axis system can be studied using reference frames connected with the moving vehicle and platform, which are shown in Fig. 4.

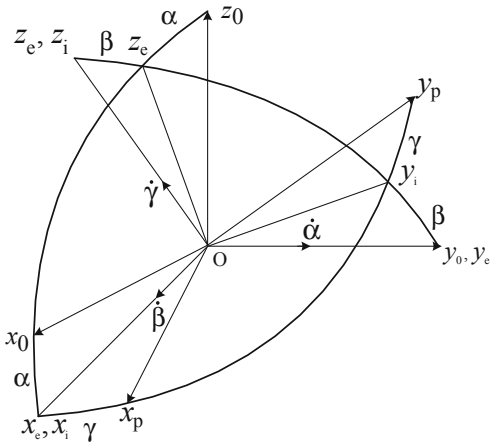

Fig. 4. The mutual position of reference frames connected with the moving vehicle and platform: $Ox_0y_0z_0$ is the reference frame connected with the moving vehicle; $Ox_py_pz_p$ is the reference frame connected with the platform; $Ox_ey_ez_e$ is the reference frame connected with the external gimbal, and $Ox_iy_iz_i$ is the reference frame connected with the internal gimbals.

The main tasks solved by ISP operated on moving vehicles include:

1) stabilization of observation equipment in the vertical, horizontal, and lateral planes during angular motion of the vehicle;
2) tracking of the line-of-sight of the observation equipment for both immovable and moving reference points;
3) combination of two previous tasks.

In accordance with Fig. 4, expressions for determining the platform's angle rates may be represented in the following way [13]

$$\begin{aligned} \omega_x &= \dot{\beta}\cos\gamma + \dot{\alpha}\cos\beta\sin\gamma, \\ \omega_y &= \dot{\alpha}\cos\beta\cos\gamma - \dot{\beta}\sin\gamma, \\ \omega_z &= \dot{\gamma} - \dot{\alpha}\sin\beta, \end{aligned} \tag{2}$$

here α, β, γ are angles of the deviations from the horizontal plane and the vertical axis respectively.

Based on expressions (2), differential equations, which characterize changing angular rates of the platform, become

$$\begin{aligned} \dot{\alpha} &= (\omega_x\sin\gamma + \omega_y\cos\gamma)/\cos\beta, \\ \dot{\beta} &= \omega_x\cos\gamma - \omega_y\sin\gamma, \\ \dot{\gamma} &= \omega_z + \mathrm{tg}\beta(\omega_x\sin\gamma + \omega_y\cos\gamma). \end{aligned} \tag{3}$$

Hence, Eqs. (2), (3) describe the kinematics of ISPs.

Four-axis ISPs are used when it is necessary to eliminate the effect of the lock of frames. Such a situation arises if at least two angles of the stabilized platform turns vary in the wide range.

The best results in the accuracy of observation equipment could be achieved by the combination of precision stabilization, improving the accuracy of inertial measuring units, and processing of measuring information [14–16].

3 Algorithm of Robust Parametrical Optimization

It is necessary to develop space-state models for the robust parametrical optimization. Based on these models and model of the controller, we can derive a set of matrices A,B,C,D of the closed-loop system necessary for the synthesis and analysis of the control laws.

The robust parametrical optimization requires using both nominal and parametrically disturbed models. Solutions taking into account maximum and minimum parameters are true for any values, which belong to the range of permissible parameters. This assertion is true for the detectable and stabilizable systems. This situation takes place in most practical applications [17]. Usage of parametrically disturbed models allows us to take into account uncertainties in the mathematical description. These uncertainties are caused by changing parameters of the real system in some bounds and the impossibility to represent all the features of the real system in a mathematical way. Commonly, such uncertainties are separated into two types as parametrical structured and unstructured (unmodelled dynamics [18]). For the parametric optimization, it is easiest to take into account parametric structured disturbances. Block diagrams of deterministic and stochastic models are shown in Fig. 5.

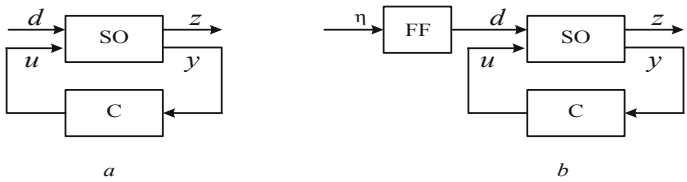

Fig. 5. Deterministic (*a*) and stochastic (*b*) models: SO is the stabilization object; C is the controller; FF is the forming filter; *d* is the signal of input; *z* is the signal of observation; *u* is the signal of control; *y* is the signal of output; η is a disturbance.

It is possible to increase the efficiency of the robust optimization using the mixed H_2/H_∞ approach [19]. The combination of H_2 and H_∞ optimizations allows us to state the task of designing optimal stabilization systems on the basis of the quadratic criterion while maintaining its properties under the influence of disturbances [80]. In this case, the optimal synthesis should be carried out using a combined optimization criterion taking into account both the quality and the robustness of ISP [20].

Such a criterion is determined on the basis of H_2, H_∞ norms. The influence of each component can be regulated by weighting coefficients, which depend on the characteristics and features of the system. For designing robust systems, it is advantageous to apply the complex criterion founded on accuracy indices of nominal and perturbed systems. In this case, the parametric structured perturbations are taken into account. Hence, the complex objective function takes the form [11, 20]

$$\begin{aligned} J_{H_2/H_\infty} &= \lambda_2^{\text{nom d}} ||\Phi(K,x,u,j\omega)||_2^{\text{nom d}} + \lambda_2^{\text{nom s}} ||\Phi(K,x,u,j\omega)||_2^{\text{nom s}} + \\ &+ \lambda_\infty^{\text{nom}} ||\Phi(K,x,u,j\omega)||_\infty^{\text{nom}} + \sum_{i=1}^{n} \lambda_{2_i}^{\text{par d}} ||\Phi(K,x,u,j\omega)||_{2_i}^{\text{par d}} + \\ &+ \sum_{i=1}^{n} \lambda_{2_i}^{\text{par s}} ||\Phi(K,x,u,j\omega)||_{2_i}^{\text{par s}} + \sum_{i=1}^{n} \lambda_{\infty i}^{\text{par}} ||\Phi(K,x,u,j\omega)||_{\infty_i}^{\text{par}} + PF, \end{aligned} \tag{4}$$

here $||\cdot||_2^{\text{nom d}}$, $||\cdot||_2^{\text{nom s}}$, $||\cdot||_{2_i}^{\text{par d}}$, $||\cdot||_{2_i}^{\text{par s}}$ are H_2-norms of transfer functions of the deterministic and stochastic systems with nominal and parametrically disturbing parameters, $||\cdot||_\infty^{\text{nom}}$, $||\cdot||_{\infty_i}^{\text{par}}$ are H_∞-norms of transfer functions of the nominal and parametrically disturbed systems, $\lambda_2^{\text{nom d}}$, $\lambda_2^{\text{nom s}}$, $\lambda_\infty^{\text{nom}}$, $\lambda_{2_i}^{\text{par d}}$, $\lambda_{2_i}^{\text{par s}}$, $\lambda_{\infty_i}^{\text{par}}$ are weighting coefficients of appropriate norms, *n* is the number of the system's models, *PF* is the penalty function that ensures fulfillment of a system's stability conditions at the time of the optimization procedure, K is a vector of optimized parameters.

Consider constituents of the objective function (4). The weight coefficients in the deterministic case are calculated on the ground of Gramian of controllability. Usage of H_∞-norms of models with parametrically disturbed parameters in the objective function ensures a certain insensitivity of the synthesized system to changing parameters in the range of the acceptable values. It is common knowledge [17, 20] that requirements for performance and robustness are mutually contradictory. Hence, the problem of the H_2/H_∞ synthesis of the stabilization system asserts in searching for a compromise between performance and robustness. This compromise can be ensured through the use

of the combined objective function with changing weight coefficients (4). Such technique permits a researcher to decrease or increase the level of performance or robustness during design of the system.

The search for a solution requires the multiple minimizations of the objective function (4) using one of the well-known techniques. For control or stabilization systems, it is expedient to use the non-strict Nelder-Mead method or the genetic algorithm [21]. The preference of the latter algorithm asserts the possibility to obtain the global minimum in contrast to the Nelder-Mead method.

The heuristic procedure of robust optimization is carried out in two phases.

Solutions admissible in the view of technical performances are determined at the first phase. At this phase, constituents of the vector Λ are considered to be units. For some given values of matrices Q and R, it is necessary to implement minimization of the criterion (4). After fulfillment the optimization procedure, it is necessary to check functional constraints. If these constraints are not satisfied, it is necessary to increase weight coefficients q_i (for condition $x_i > x_{i0}$) and r_j (for condition $u_j > u_{j0}$). The optimization procedure is repeated until the functional constraints will be satisfied. The obtained solutions are permissible from the point of view fulfillment requirements that are given to control systems.

At the second phase, elements of matrices Q and R are believed to be fixed. And weighting coefficients (vector Λ) are varied.

It should be noted that both phases are implemented in the interactive mode.

A compromise between indices of accuracy and robustness is defined by a researcher, which could give a preference one of the criteria depending on operation conditions and constructive features of the designed system. For example, the preference must be given to the component $J^s_{H_2}$ for the influence of intense random external disturbances. In conditions of significant parametric disturbances, it is advisable to decrease the objective function J_∞.

Based on the results of practical applications, we can say that some cycles of the above-mentioned optimization procedure ensure a desired compromise.

It is worth considering that the described approach is characterized by a heuristic nature. There is no way to prove it convergence in an analytical way. But its efficiency is proved by the great quantity of the practical applications.

The block diagram of the algorithm of designing a stabilization system based on the parametrical robust optimization is represented in Fig. 7.

The algorithm of robust parametrical optimization is characterized by some features. It should be noted that a model of the control system can have non-controlled and non-observable parts. In this case, it is necessary to simplify the model that is to determine its minimum realization. There are two approaches to the implementation of the minimum realization [22].

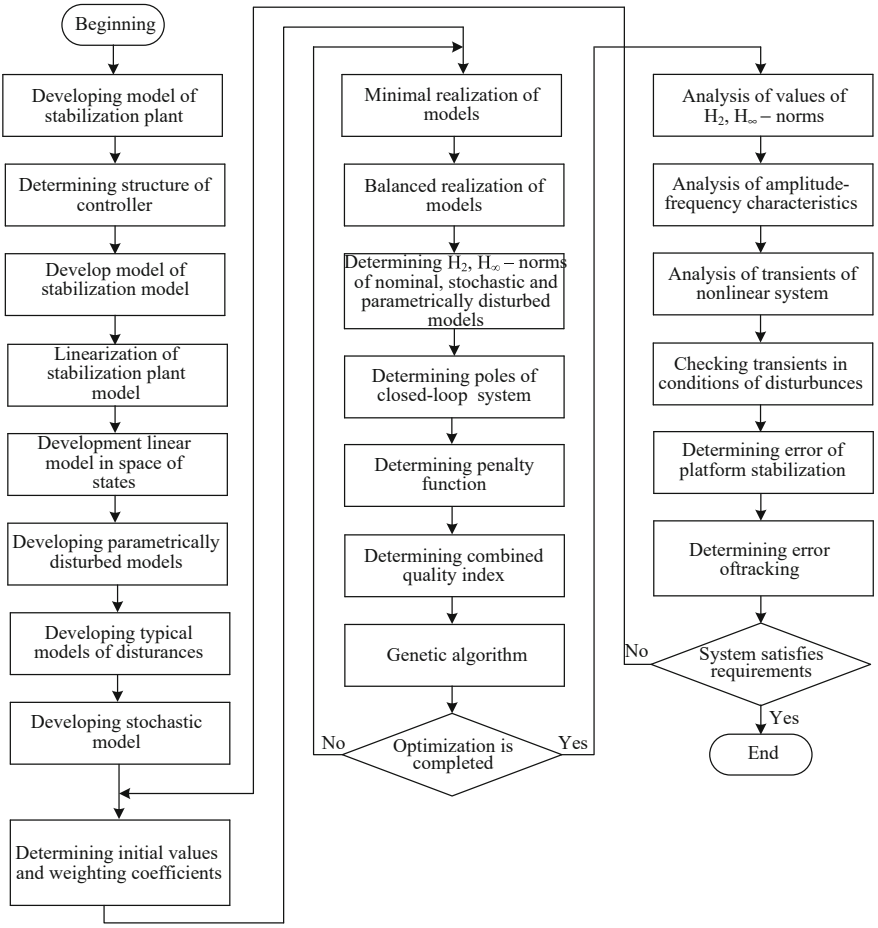

Fig. 6. The algorithm of designing inertially stabilized platform using the robust parametrical optimization.

The first approach is based on using non-minimum realization in the space of states, which is formed on the basis of the model, which corresponds to the real system. Further, the obtained model is reduced to observable and controllable parts.

The second approach is based on using impulse characteristics of the system and obtaining the minimum realization by the transformation of the Hankel matrices. In our situation, it is expedient to use the first approach as impulse characteristics of the system are not always known at beginning of the design process. The review of known algorithms gives grounds to choose the Rosenbrock algorithm. It should be noted that minimum realization can be implemented by MatLab software [23–26].

In some applications, it is expedient to use astatic control systems. In this case, we can use a shift of the matrix of state-space model [25]. In such a way, it is possible to avoid the appearance of the zero poles that is of great importance for astatic systems. The shifted matrix looks like $A_{sh} = A\text{-}A_0$, where A_0 is the matrix with some small elements. Usage of such an approach leads to to obtaining the balanced realization.

For industrial applications, models of control systems very often are characterized by sufficient dispersion of elements. Usually, the state-space matrices are believed to be ill-conditioned. To eliminate this disadvantage, it is necessary to use scaling. For this, it is possible to use the balanced realization or a realization with equal Gramians of controllability and observability [22].

4 Algorithm of Robust Structural Synthesis

The modern approach to designing ISPs foresees usage of robust structural synthesis. One of the widespread methods is H_∞-synthesis, which ensures designing in conditions of uncertainty. It is known, that the designing of real systems must satisfy some conflict purposes. Research of a compromise in this situation can be achieved by the usage function of mixed sensitivity for forming the optimization objective function. It is also convenient to use two control loops by the reference signal and by the disturbance. Such systems are called two-degree-of-freedoms systems. There are different approaches for their designing. The method supposed in [17] is grounded on the robust stabilization and representation of the parametrical disturbances using the normalized co-prime factorization. It is based on loop shaping that is forming the required frequency responses of the designed ISP. After forming the stabilization object with desired characteristics, it is possible to synthesize H_∞-controller, which ensures the robust stability and robust performance of the designed system [27].

The advantages of the above-mentioned approach are ensuring robust stabilization and taking into account parametrical disturbances. It should be noted, the influence of coordinate perturbations in practical applications is essential. The method of improving the above-mentioned procedure is based on introducing components connected with external disturbances in the optimization criterion, as this has been supposed in [6, 28] – [30]. The optimization criterion for H_∞-synthesis becomes

$$J = \left\| \begin{array}{cc} -W_1T_{ref}+ & W_1G_d(1+GK_2)^{-1} \\ +W_1GK_1(I+GK_2)^{-1} & \\ W_2K_1(I+GK_2)^{-1} & -W_2K_2G_d(I+GK_2)^{-1} \\ W_3GK_1(I+GK_2)^{-1} & W_3G_d(I+GK_2)^{-1} \end{array} \right\|_\infty, \quad (5)$$

here W_1, W_2, W_3 and T_{ref} are weighting and reference transfer functions, G, K_1, K_2, G_d are transfer functions of the plant, controllers, and disturbance.

The models of disturbances were developed after analysis of the features of the system. For example, for the ISPs operated on the ground moving vehicles, it is expedient to take into account the imbalance moment and disturbances caused by the angular rate

of the ground moving vehicle [6]. Further, it is necessary to develop the mathematical model of the generalized augmented system taking into account both parallel and serial connections of the system's units [28]. Equations of state and observation become

$$\begin{aligned}
\dot{x}_G &= A_G x_G - B_G u + B_{G_d} d, \\
\dot{x}_{Tef} &= A_{T_{ref}} x T_{ref} + B_{T_{ref}} r, \\
\dot{x}_{W_1} &= A_{W_1} x_{W_1} - B_{W_1} u + B_{W_1} r, \\
\dot{x}_{W_2} &= A_{W_2} x_{W_2} - B_{W_2} u, \\
\dot{x}_{W_3} &= A_{W_3} x_{W_3} - B_{W_3} u + B_{W_3} r, \\
z_1 &= C_{W_1} x_{W_1} + D_{W_1} r, \\
z_2 &= C_{W_2} x_{W_2} + D_{W_2} u, \\
z_3 &= C_{W_1} x_{W_3} + D_{W_3} u + D_{G_d} d, \\
y_1 &= r, \\
y_2 &= D_G u + D_{G_d} d,
\end{aligned} \tag{6}$$

here, x, z, y, u represent signals of state, observation, output, and control; A, B, C, D are matrices of the state, control, observation, and disturbance in the space of states.

The model in the space of states looks like

$$\mathrm{P} = \begin{bmatrix}
\mathrm{A_G} & 0 & 0 & 0 & 0 & 0 & \mathrm{B_{G_d}} & \mathrm{B_G} \\
0 & \mathrm{A_{T_{ref}}} & 0 & 0 & 0 & \mathrm{B_r} & 0 & 0 \\
-\mathrm{B_{W_1}} & 0 & \mathrm{A_{W_1}} & 0 & 0 & \mathrm{B_{W_1}} & 0 & -\mathrm{B_{W_1} D_G} \\
0 & 0 & 0 & \mathrm{A_{W_2}} & 0 & 0 & 0 & \mathrm{B_{W_2}} \\
\mathrm{B_{W_3} C_G} & 0 & 0 & 0 & \mathrm{A_{W_3}} & \mathrm{B_{W_3}} & 0 & \mathrm{B_{W_3} D_G} \\
-\mathrm{D_{W_1} D_G} & 0 & \mathrm{C_{W_1}} & 0 & 0 & \mathrm{D_{W_1}} & 0 & \mathrm{D_{W_1} D_G} \\
0 & 0 & 0 & \mathrm{C_{W_2}} & 0 & 0 & 0 & \mathrm{D_{W_2}} \\
\mathrm{D_{W_3} C_G} & 0 & 0 & 0 & \mathrm{C_{W_3}} & 0 & \mathrm{D_{G_d}} & \mathrm{D_{W_3} D_G} \\
0 & 0 & 0 & 0 & 0 & \mathrm{I} & 0 & 0 \\
\mathrm{C_G} & 0 & 0 & 0 & 0 & 0 & \mathrm{D_{G_d}} & \mathrm{D_G}
\end{bmatrix}. \tag{7}$$

H_∞-synthesis can be implemented by MatLab software [31, 32]. In contrast to the known approaches, we propose to take into consideration the influence of the external disturbances.

The block diagram of H_∞-synthesis of ISP is represented in Fig. 8. Expressions (5) – (7) are the mathematical grounds of the algorithm.

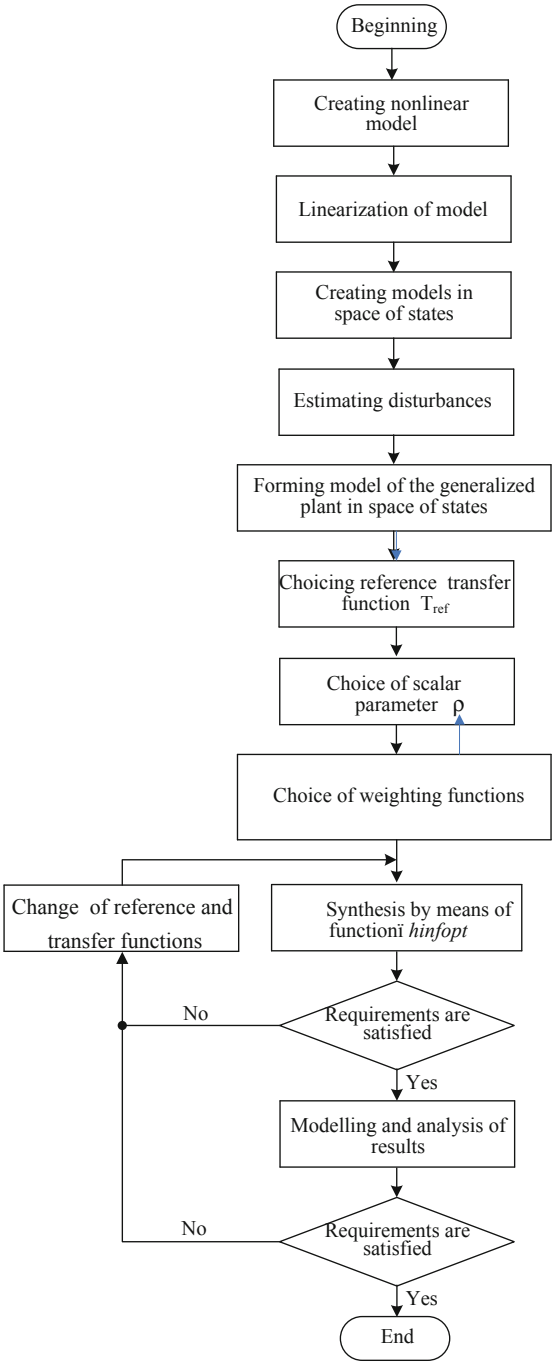

Fig. 7. The algorithm of the robust structural synthesis.

5 Simulation Results

The numerical calculation has been carried out on the example of designing ISPs assigned for operation on the ground moving vehicle with the nominal model.

$$A_{0g} = \begin{bmatrix} -1,62 & 0 & -3225,37 & -1,64 \cdot 10^6 & 1602,56 \\ 0 & -0,232 & 0,55 & -281,85 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -41,67 & 0 & 0 & 0 & -666,67 \end{bmatrix}$$

$$B_{0g}^{T} = \begin{bmatrix} 0 & -0,28 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 666,67 \end{bmatrix}$$

The results of the parametrical robust optimization are given in Fig. 9.

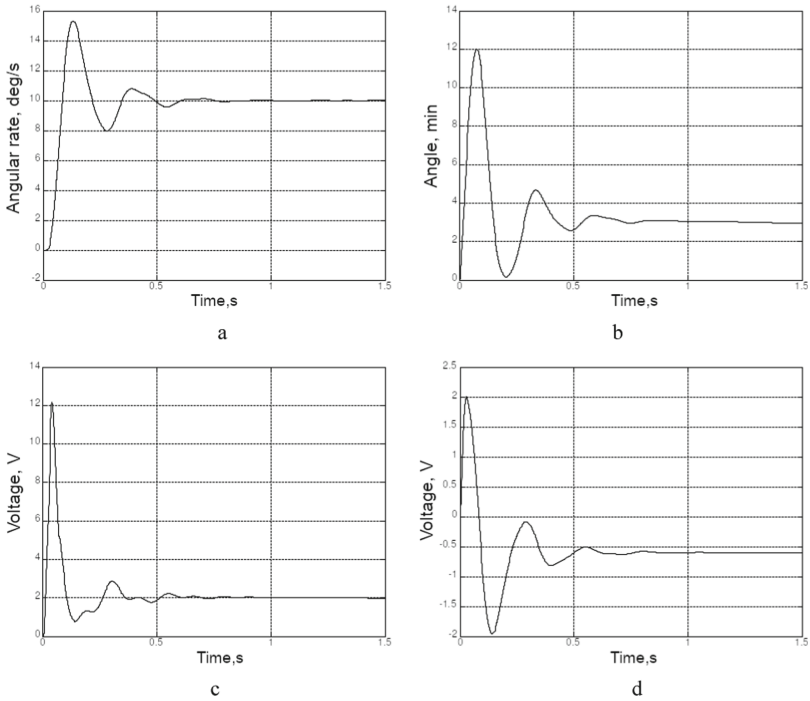

Fig. 8. Simulation results: a is the transient process of the angle rate; b is the transient process of angle position; c is the transient process of the electric motor angle rate; d is the transient process of feedback by the current.

It should be noted that this task can be accomplished by automated tools of the Robust Control Toolbox.

Results of H_∞-synthesis of the two-degrees-of-freedom system are shown in Fig. 10. The represented graphs prove the advantages of robust systems in conditions of significant parametric disturbances (±50%).

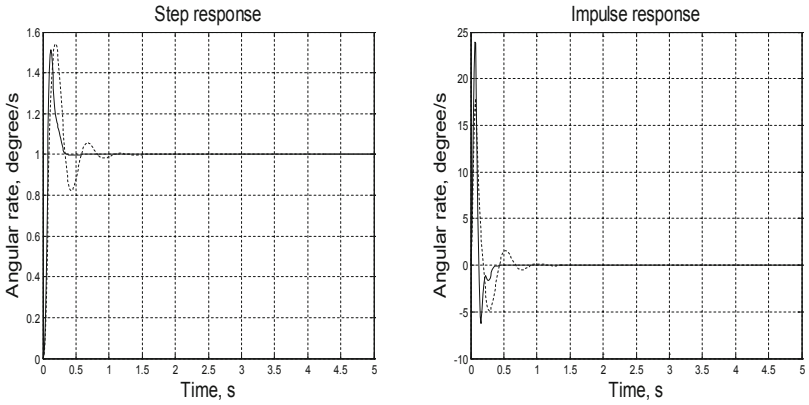

Fig. 9. Reaction on the step and impulse signals for increased moment of inertia

6 Discussion

Note the important feature of the proposed algorithms for designing stabilization systems, which can successfully function on moving vehicles. The usage of robust control systems has advantages in comparison with adaptive systems of the cost and complexity. The proposed algorithm ensures precision and other operating performances of the stabilization systems during designing in conditions of uncertainties caused by inaccuracies in the mathematical description and the possible influence of coordinate disturbances. The necessity of improving the quality of stabilization processes is mentioned in [33–35]. The important item is the possibility of implementing proposed algorithms by MatLab software.

The main result of the research is the development of the algorithm for designing robust ISP. This algorithm ensures keeping the high precision of stabilization in conditions of real operation, which is accompanied by the influence of the external disturbances. The research improves the quality of stabilization systems operated on vehicles.

7 Conclusions

The classification of ISPs is given.

The algorithm of the robust parametrical optimization is represented. The features of this algorithm including the necessity of the minimum and balanced realizations, usage of the genetic algorithm are described.

The numerical algorithm of designing the robust structural system with the two-degrees-of-freedom has been developed. The optimization criterion using the sensitivity function by the external disturbances has been supposed. The expression for the optimization criterion and the model in the space of states are represented.

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